TIME DEPENDENT BEHAVIOUR OF FROZEN PELLETIZED TAILINGS IN UNDERGROUND MINES

FINAL REPORT

BY

NANTAR ENGINEERING LIMITED

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SUMMARY

A laboratory test program was conducted to evaluate those parameters of frozen slurried and pelletized tailings critical to their use as an engineered underground mine backfill. The test procedure was designed to simulate underground conditions. Tailings materials were obtained from three Canadian gold and base metal mines. An initial series of characterization tests were performed on each tailings materials including grain size distribution, bulk density, true solids density, porosity, and particle shape analysis.

Frozen short term strength tests were conducted on each material in order to determine the instantaneous unconfined compressive strength. The dynamic tests indicated a much lower strength for frozen pelletized samples than for frozen slurried tailings.

Constant load tests were then done at various percentages of the unconfined compressive strength; in this project, levels equivalent to 30% and 50% of the failure load were used.

The constant load tests were performed in two distinct phases in order to simulate in-situ mine conditions. In the first phase, samples were tested in a confined condition to simulate full stope confinement. Confined tests were continued until constant deformation-time rates were obtained. Confinement was then released to simulate pillar extraction.

It is concluded that frozen pelletized mine tailings is not a competent backfill material if the recovery of pillars is contemplated. Frozen slurried tailings could remain exposed over heights reaching 75 m; the placement and in-situ freezing of such material though would present several technical difficulties.

SOMMAIRE

Un programme d'essais en laborataire a été entrepris pour évaluer les paramêtres qui rendraient l'utilization des rejets de concentrateur gelés, en vrac ou sous forme de boulettes propices à l'utilization de ceux-ci comme matériel de remblai dans les mines souterraines. La procédure suivie durant les essais fût conçue de façon à simuler les conditions existant sous-terre. Des rejets de concentrateur furent obtenus de trois mines d'or et de métaux de base. Une série initiale de tests furent faits en vue de déterminer les propriétés physiques des échantillons, notamment: la grosseur des particules, densité en place, densité des particules solides, porosité et la forme des particules.

Des essais courte-durée furent faits avec des échantillons de chaque types de rejets afin de déterminer la résistance en compression uniaxiale instantanée. Les tests dynamiques révélèrent que les échantillons gelés à partir de pulpe démontraient une résistance instantanée supérieure aux échantillons gelés faits à partir de boulettes.

Des tests furent ensuite faits avec des charges continues qui n'atteignaient que 30% et 50% de la résistance en compression uniaxiale instantanée. Les tests avec charge continue furent faits en deux phases distinctes pour pouvoir simuler les conditions minières in-situ. Dans la première phase, des échantillons furent testés avec confinement pour simuler le minage des chantiers primaires. Le confinement fût maintenu jusqu'ce que la phase déformation-temps se stabilize. Le confinement fût dès lors enlevé afin de simuler l'extraction des piliers.

Il fût conclu qu'un remblai fabriqué à partir de rejets boulettés gelés n'est pas un remblai adéquat si l'on se propose de faire l'extraction des piliers ultérieurement. La pulpe gelée pourrait a fortiori être exposée sur des hauteurs pouvant atteindre 75 m; l'emplacement de cette pulpe avec congélation subséquente présente toutefois de nombreux problèmes techniques.

TABLE OF CONTENTS

		PAGE
EXECUTIVE SUMMARY	.....	1
1.0 INTRODUCTION	.....	3
2.0 TERMS OF REFERENCE	.....	5
3.0 THEORETICAL ASPECTS	.....	6
3.1 Generalities	.....	6
3.2 Mechanical Properties of Frozen Soil and Ice	.....	6
3.3 Creep Model	.....	8
3.4 Failure Analysis	.....	15
4.0 LABORATORY APPARATUS AND PROCEDURES	.....	17
4.1 Generalities	.....	17
4.2 Backfill Physical Property Characteristics	.	17
4.2.1 Size Distribution Analysis	.....	17
4.2.2 Bulk Density, True Solids Density and Porosity Analysis	.....	18
4.2.3 Particle Shape Distribution	.....	20
4.3 Short Term Strength	.....	20
4.3.1 Slurry Samples	.....	23
4.3.2 Pelletized Samples	.....	24
4.4 Creep Tests	.....	24
4.4.1 Slurry Samples	.....	26
4.4.2 Pelletized Samples	.....	26
5.0 TEST RESULTS	.....	29
5.1 Generalities	.....	29
5.2 Short Term Strength	.....	29
5.3 Constant Stress Tests	.....	32
5.3.1 Frozen Slurried Samples	.....	32
5.3.2 Frozen Pelletized Samples	.....	37
6.0 CONCLUSIONS AND RECOMMENDATIONS	.....	46
BIBLIOGRAPHY	.....	53

1.0 INTRODUCTION

Mine backfill is used to provide ground control for pillar extraction operations. To prevent, or control, caving and total hangingwall to footwall closure as the pillars are mined, the primary stopes are backfilled with a suitable material. Backfill, however, is never as strong nor rigid as the ore it replaces so pillar mining must be properly sequenced to avoid high stress readjustments to areas immediately adjacent to current mining. As pillars are mined, backfill material provides two main functions: i) to maintain stope wall integrity as individual pillars are extracted, and (ii) to reduce the effects of long-term ground subsidence. The strength and self-weight of the backfill resists wall sloughing and basal heave in stopes, thus reducing waste dilution. Also, by filling empty voids caving rock will cease unravelling because it has limited void space to cave in to.

Consolidation of tailings backfill is done in operations where pillar ore is removed during secondary mining operations. Cement is added in various percentages to sand backfill to act as a binding agent and to achieve the necessary consolidation. With cement addition to backfill adjacent blasting energy is absorbed without mass failure. Also, the danger of fill liquefaction is eliminated and the fill may be designed as a free-standing structure over the height of face exposed as pillars are removed. A major drawback of employing cemented backfill, however, is one of cost. Isolated mining operations, particularly mines in the far north, incur high costs for cement shipped from major industrial centres. Furthermore, many mines do not possess a suitable mill tailings material for placement underground. This occurs for various reasons including high slimes content, poor percolation and strength characteristics or health reasons. A major problem associated with arctic mining operations situated in permafrost ground is one of ground thaw. Tails and water slurries expelled from the mill are warm and when introduced underground they can cause serious support problems to the frozen host rock if pore ice begins to melt.

For the above reasons the potential application for frozen tailings has begun to receive some attention. The short-term strength of this material in a confined mode has been shown to be more than adequate. Both frozen slurry and frozen pelletized

slurry, for ease of handling, have been previously tested producing good results when compared to cemented tailings fill.

The purpose of this study is to analyze both frozen slurry and frozen pellet materials with regards to in-situ stability parameters and long-term strength. The present study is comprised of tests that most suitably model the engineering application of frozen tailings. A long-term strength model was chosen that closely reflects the actual sequence of events that occur when removing underground pillars adjacent to mine manufactured frozen backfill. This model includes the manufacturing, placement and in-situ consolidation of frozen materials in both slurry and pellet forms, at temperatures likely to exist in arctic mining operations. It then attempts to simulate in-situ load and deformation conditions as adjacent confining pillars are removed.

2.0 TERMS OF REFERENCE

An unsolicited proposal to Supply and Services Canada was submitted on November 28, 1983. A contract agreement was signed on July 31, 1984 and work commenced immediately. The terms of the contract were for a 12 month period and the work to be supervised by a representative of CANMET of the Department of Energy, Mines and Resources. The present report outlines the results of the work carried out under the above mentioned contract agreement.

3.0 THEORETICAL ASPECTS

3.1 Generalities

For engineering applications where the performance of a structure depends upon the strength and deformation characteristics of the in-situ frozen material, long term, low strain rate (creep) behaviour, must be determined. This is done by testing samples under conditions that are expected to prevail during the life of the structure. An appropriate theory or curve-fitting procedure is then used to give a constitutive equation suitable for use in the analysis and prediction of structural performance. Both empirical curve-fitting methods and engineering theories for creep and failure are presented in this section.

3.2 Mechanical Properties of Frozen Soil and Ice

Relatively large loads can be supported by frozen soils since they exhibit strengths comparable to that of weak concrete. In relatively warm, fine-grained, frozen soils the application of high loads may produce volume changes upon consolidation. Engineering design requires that maximum load capabilities be determined and that settlement of the material not exceed certain limits. Laboratory testing provides information on frozen soil parameters needed for constitutive equations.

The strength of frozen soils develops from cohesive, interparticle friction and particle interlocking, much as in unfrozen soils. The primary difference between the strengths of frozen and unfrozen soils is derived from the ice component. Cohesive forces are produced by the adhesive strength mobilized between the soil particles and the ice, filling the empty voids, as well as surface forces between the particles. At low solids concentrations (ice-rich) the strength and mechanical behaviour of frozen soils will approximate that of ice. At high solids concentations (ice-poor), interparticle friction and dilatancy characterize the soil strength. In a typical sand/ice material, for low volume fractions of sand, the increase in shear strength varies linearly with the relative proportions of sand and ice, as shown in Figure 3.1. A rapid increase in shear strength is observed to occur when a critical volume fraction of sand is

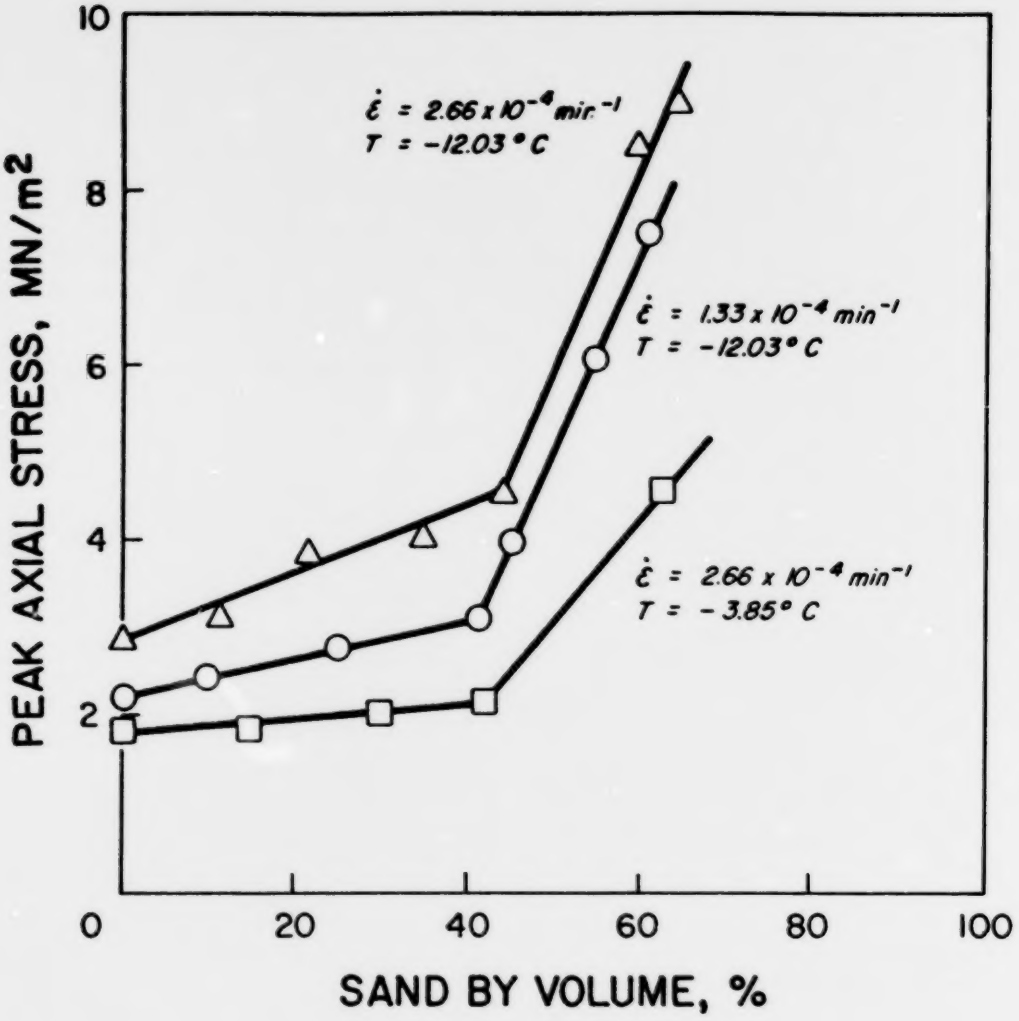


FIGURE 3.1: VOLUME CONCENTRATION OF OTTAWA SAND AND PEAK STRENGTH (FROM ANDERSLAND AND ANDERSON, 1978)

reached, at about 42 percent.

Frozen soil strength is also sensitive to strain rate, temperature, confining pressure, particle size, particle orientation and packing conditions, and also to the presence of any impurities in the water-ice matrix. Figure 3.2 shows the effect of temperature on the unconfined compressive strength of a variety of frozen soils and ice. Figure 3.3 shows that, over a range of strain rates from about 10^{-5} to 10^{-2} sec^{-1}, the unconfined strength of frozen Ottawa sand would be expected to almost double. The above data indicates the sensitivity of ice and frozen soil strength to environmental factors.

3.3 Creep Model

Research on the creep of frozen soils has followed two paths. One considers the physical theory capable of describing creep behaviour in terms of established physical laws or properties of matter. The other approach seeks an engineering theory of creep to be used in design. This theory can be considered as a collection of laws that are known to describe the creep behaviour of frozen soils adequately through experience. Emphasis in this report is placed on the engineering theory.

The dominance of creep characteristics under applied constant load and the rate dependence of strength are unique features of the mechanical properties of frozen soils. The rate effects are temperature and load dependent and vary with the amount of ice present in the soil.

When a frozen soil is subjected to a load it will respond to exhibit both an instantaneous and a time-dependent deformation component. If the load is sufficiently great it will exhibit a limiting strength. The creep curves shown in Figure 3.4, obtained by step loading under uniaxial stress conditions at constant temperature, are common to a large number of materials including frozen soils, plastics and many metals at high temperature. Figure 3.5 presents the corresponding creep rate, $d\varepsilon/dt$, versus time, t, information for detailed analysis. Three periods are observed during which the creep rate is shown to be (I) decreasing, (II) constant and (III) increasing. These are commonly referred to as primary, secondary and tertiary creep.

Figure 3.6 illustrates a set of creep curves obtained in a

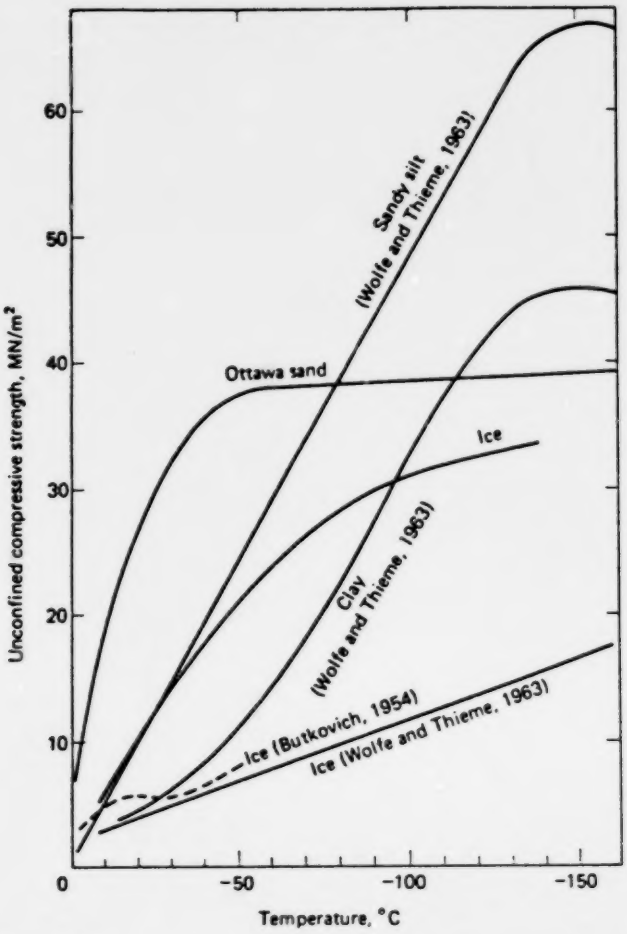


FIGURE 3.2: TEMPERATURE DEPENDENCE OF UNCONFINED COMPRESSIVE STRENGTH FOR SEVERAL FROZEN SOILS AND ICE (AFTER SAYLES, 1966)

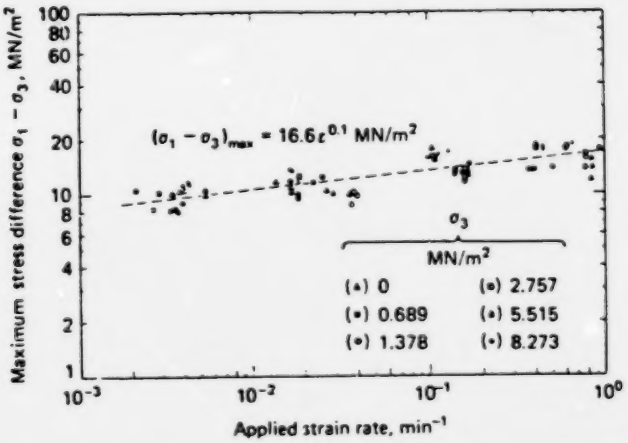


FIGURE 3.3: STRENGTH VERSUS APPLIED STRAIN RATE FOR OTTAWA SAND (AFTER SAYLES, 1973)

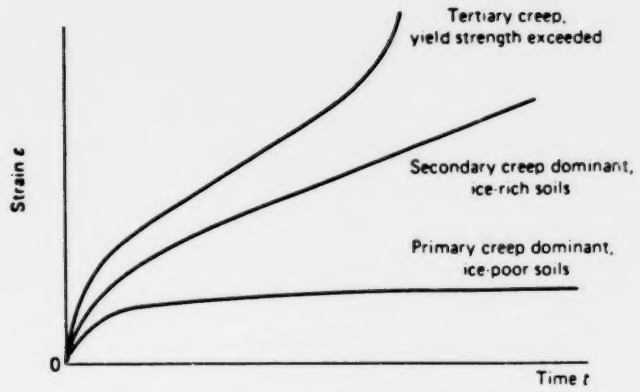


FIGURE 3.4: SEVERAL TYPICAL CREEP CURVES (AFTER ANDERSON & ANDERSLAND, 1978)

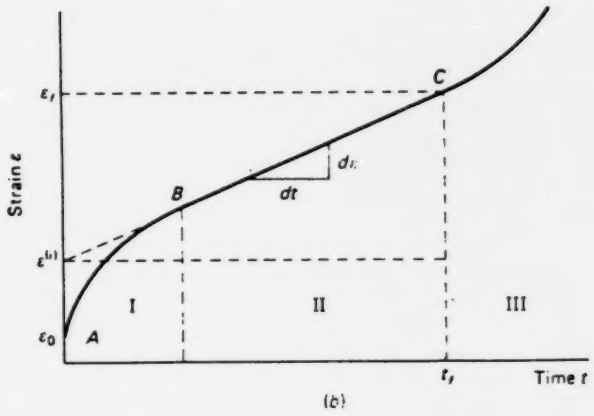


FIGURE 3.5: TYPICAL STRAIN VERSUS TIME CURVE (AFTER ANDERSON AND ANDERSLAND, 1978)

series of constant temperature creep tests, step loaded to different uniaxial stress levels of $\sigma_1 < \sigma_2 < \sigma_3 < \sigma_4$.

A convenient method for establishing the constitutive equation of a material can be described for the creep curves shown in Figure 3.6. The creep curves are approximated by straight lines having intercepts as shown. At constant stress and temperature secondary creep strain may be represented by:

$$\varepsilon = \varepsilon^{(i)} + \varepsilon^{(c)} \qquad 3.3.1$$

where the pseudoinstantaneous strain $\varepsilon^{(i)}$ is governed by:

$$\varepsilon^{(i)} = F(\sigma,T) \qquad 3.3.2$$

and the creep strain $\varepsilon^{(c)}$ by the creep law

$$\frac{d\varepsilon^{(c)}}{dt} = G(\sigma,T) \qquad 3.3.3$$

The form of the functions $F(\sigma,T)$ and $G(\sigma,T)$ is determined by first plotting the intercepts, $\varepsilon^{(i)}$, and the slopes, $d\varepsilon^{(c)}/dt$, against the applied stress, as shown in Figure 3.7. Thereafter, suitable mathematical expressions are fitted to the experimental curves with temperature being held as a constant parameter.

Once the mathematical form of the functions, F and G, have been determined, the total strain after time, t, in a creep test, step loaded to a stress, σ, at constant temperature, is given by:

$$\varepsilon = F(\sigma,T) + G(\sigma,T)t \qquad 3.3.4$$

The strain in a creep process in which the load is increased in steps, σ, and the temperature, T, is held constant for each step, is obtained by a summation as shown in Figure 3.8. At time, t, the total strain is a function of the complete loading and temperature history of the process.

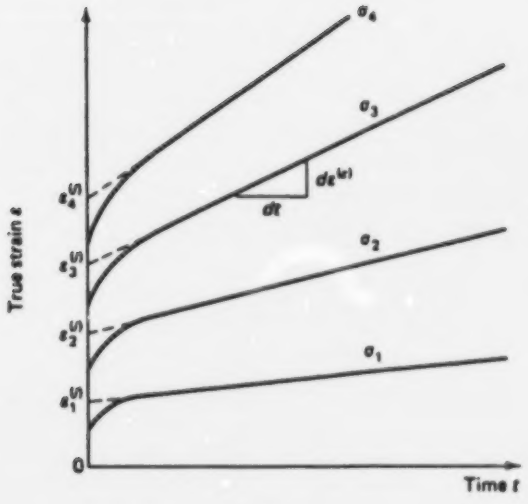


FIGURE 3.6: SERIES OF CREEP CURVES OBTAINED FOR CONSTANT TEMPERATURE, VARIABLE LOADING CONDITIONS (AFTER ANDERSON AND ANDERSLAND, 1978)

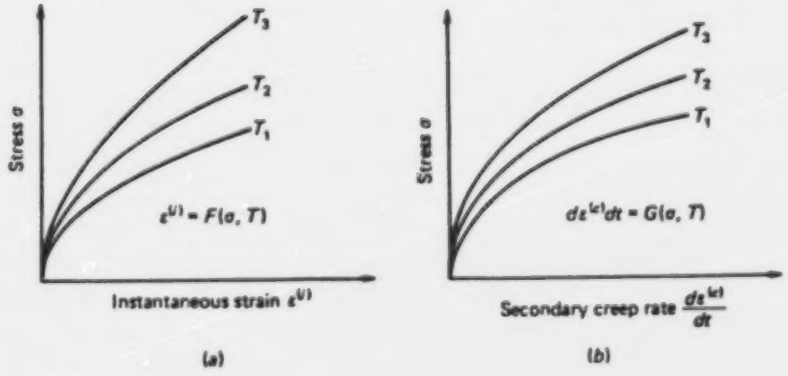


FIGURE 3.7: CONSTANT TEMPERATURE CURVES: a) STRESS VS. INSTANTANEOUS STRAIN; b) STRESS VS. CREEP RATE (AFTER ANDERSON AND ANDERSLAND, 1978)

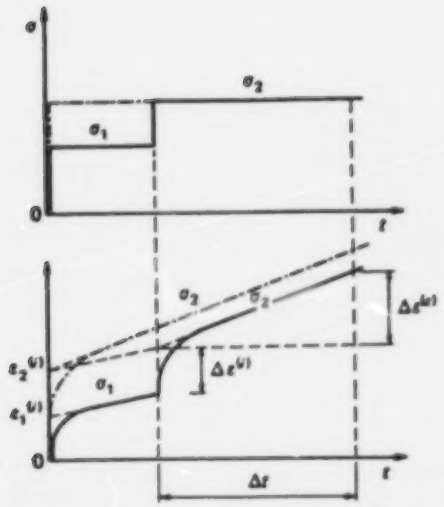


FIGURE 3.8: CREEP CURVES FOR STEP LOADING CONDITIONS (AFTER LADANYI, 1972)

The total creep can be expressed by the general empirical relationship:

$$\varepsilon_t = \varepsilon_e + \varepsilon_d + \varepsilon_v \qquad 3.3.5$$

where, ε_t is the total creep deformation realized, ε_e and ε_d, which together represent the pseudo-instantaneous strain, are the pure elastic (reversible) strain and plastic (irreversible) strain components respectively, and ε_v represents the permanent creep strain. In its integrated form it may be expressed in terms of parameters of stress, σ, and time, t, for a material at a constant temperature, T, by the relationship:

$$\varepsilon_t = \sigma/E + \varepsilon_k \left(\frac{\sigma}{\sigma_k}\right)^k + \dot{\varepsilon}_c \left(\frac{\sigma}{\sigma_c}\right)^n t \qquad 3.3.6$$

In this equation the three terms correspond to the three successive terms in the previous equation.

In the equation, the symbol, E, represents a fictitious Young's Modulus which will be smaller than the instantaneous elastic modulus due to a delayed elasticity effect; σ_K, a temperature dependent deformation modulus; the exponents, K<1, are constants obtained from a log-log plot of the pseudo-instantaneous stress-strain curve; σ_c and n are creep parameters obtained from a log-log plot of experimental stress-strain rate curves; and $\dot{\varepsilon}_c$ is a small arbitrary standard strain rate introduced to put equation 3.3.6 in a normalized form.

It can be shown that for time intervals greater than about 24 h the two instantaneous strain terms together become less than 10% of the creep strain. Therefore, for time intervals longer than about one day it is sufficient, for practical purposes, to use the third term of equation 3.3.6 only. Thus,

$$\varepsilon \simeq \varepsilon_c t \left[\frac{\sigma}{\sigma_c(T)}\right]^n . \qquad 3.3.7$$

If the necessary parameters can be determined from laboratory testing of representative materials, equations such as 3.3.7 can

then be used to evaluate the deformation capabilities of frozen materials, at particular loads and temperatures, with time.

Such analysis would appear applicable to determine frozen fill response during pillar extractions.

3.4 Failure Analysis

To analyze frozen backfill free standing height capabilities one must determine both the shear strength parameters of the material acting at the rock interface and the shear strength parameters with the material matrix.

Studies performed by Weaver and Morgenstern (1981) on frozen material shear resistance have shown that when the asperities of smooth plates are filled with air or supercooled water, the shear plane which is induced between plates is not forced through the ice itself. If however the ice follows the contours of the asperities, one will expect resultant shear failure to be forced through the ice. After similar tests, using frozen silt as the bonding element between plates, it was found by Morgenstern that the shear strengths increased. The higher strength may be attributed to solid particle interaction creating additional frictional resistance along the plane of shear. Also, it was postulated that this only existed if the freezing front progressed from the soil to the plate during preparation. If this front travelled in the opposite direction, a thin layer of ice would form at the plate/soil interface and the failure mechanism would be characteristic of an ice failure mechanism. Morgenstern concluded, therefore, that adhesive shear failure is a function of the ice contact at the interface and the local geometry of the asperities or irregularities on the interface (roughness). A critical plate roughness may also exist, above which the frozen material will fill the irregularities thereby increasing the adhesive shear strength at the frozen medium/solid interface.

On a larger scale, in a mine void, relatively deep rock wall irregularities will characteristically produce a high roughness at the rock wall/frozen fill interface. In a stope void, backfill is supported at the bottom and is initially confined for frozen backfill application; therefore, the frozen material/rock contact will be good. That is, the intrusion depth

of the asperities into the backfill will be well established by the tendency of frozen materials to flow into wall cavities under the pressure of its own weight.

From this analysis it can be concluded that the shear strength or bond strength at the wall contact will be equal to the shear strength of the frozen material itself. That is, any shear failure will be forced through the material matrix. It is generally accepted that the unconfined compressive strength, σ_c, of typical frozen material is equal to twice the direct shearing strength, c, ($\sigma_c = 2c$). The shear strength parameter can therefore be derived from short term unconfined compression laboratory tests on representative frozen samples.

4.0 LABORATORY APPARATUS AND PROCEDURES

4.1 Generalities

All tests performed to characterize both the physical properties of the constituent tailings materials and the creep behaviour of frozen mixutres of tailings were conducted within the Rock Mechanics and Cold Environment Laboratory facilities of the Department of Mining Engineering, Queen's University at Kingston, Ontario.

Representative samples of tailings materials were obtained from three Canadian mines, namely the Gallen, Matagami and Pamour mines of the Noranda Mines Group. An initial series of characterization tests were performed upon each constitutent tailings material, including grain size distribution, bulk density, true solids density, porosity (dry) and particle shape analysis. Such tests were performed within the rock mechanics facility, where considerable backfill research is conducted on a routine basis. Upon completion of such tests, sample mixtures of the various component tailings materials were manufactured, with water additions, and frozen. Subsequent tests, performed in the Cold Environment Laboratory and general rock mechanics facility, were utilized to determine sample static and dynamic strength and deformation behaviour.

4.2 Backfill Physical Property Characteristics

Tailings material characterization was performed to determine the nature of the materials which were to be used for freezing tests.

4.2.1 Size Distribution Analysis

Each tailing sample shipped weighed approximately 200 kg, including retained moisture. Samples, as-received, were thereupon dried under room temperature conditions until consistent sample weights were achieved. Batch materials were randomly sampled to retrieve 200 g lots of representative tailings. A minimum sample population of 6-200 gram units were selected for each of the respective tailings products. Wet screening tests were then implemented to prepare oversize material retained at the 270 mesh screen size. Wet oversize

screen material was oven-dried at 60°C, and was subsequently dry screened and weighed on appropriate sieves between the 10 mesh and 400 mesh fractions.

The wet undersize material was allowed to settle and the water was decanted. Slurry which remained was then oven dried, weighed, and wet sieved through 270, 325 and 400 mesh sieves. The weight fractions and size distribution data were determined for each sample batch, and were averaged. The results of a minimum of six tests, performed on each of three different tailings products, are illustrated in the size distribution curves of Figure 4.1. The curves illustrate significant size distribution variation between each of the three various tailings raw materials, with the Pamour tailings exhibiting a generally coarser size distribution. In each case, a significant fines content was evident. The respective size fractions, finer than 400 mesh, vary between 19.5% (Gallen), 23.5% (Matagami) and 29.4% (Pamour) for the three tailings products. Due to the fineness of products, no d_{10} characterization, hence Coefficient of Uniformity (Cu), estimates were possible.

4.2.2 Bulk Density, True Solids Density and Porosity Analyses

Dry bulk density characteristics of each tailings product were determined by weighing known volumes of each within standardized measuring flasks. A minimum of twenty sample tests were performed on each material, then averaged. Bulk density results were determined to an accuracy of $\pm$ .02 g/cm^3.

Sample true solids density parameters (equivalent to specific gravity of solids) were determined within a Micromeritics Model 1302 Helium/Air Pycnometer, to a similar degree of accuracy of $\pm$ .02 g/cm^3. A minimum of ten sample tests, on each tailings product, were performed.

Sample porosity parameters were then determined according to the relationship:

$$n = 1 - \frac{\rho}{\rho_s}$$

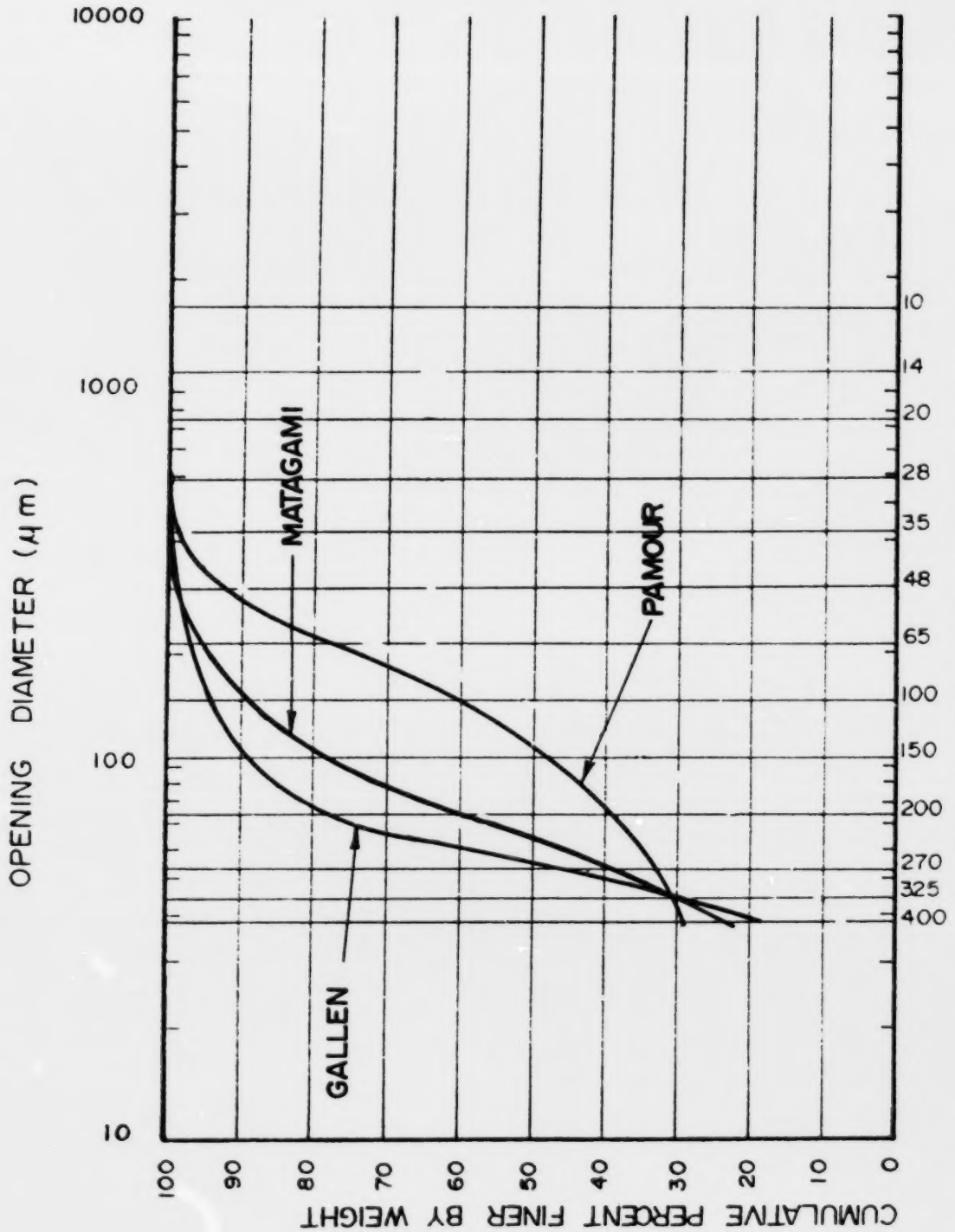


FIGURE 4.1 - AS-RECEIVED TAILINGS SIZE DISTRIBUTION CURVES

where n = porosity (fraction or percent)
ρ = dry bulk density, g/cm^3
ρ_s = true solids density, g/cm^3

A summary of physical property and size analysis data is listed in Table 4.1.

4.2.3 Particle Shape Distribution

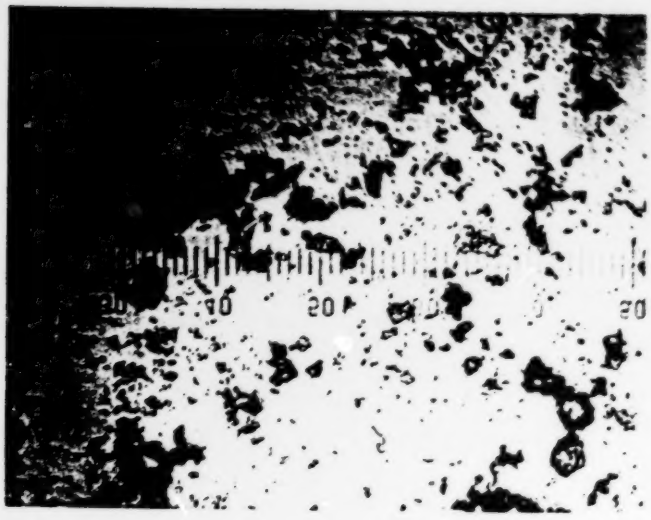
Where the backfill strength characteristics may develop from interparticle friction and particle interlocking, grain shape character may be illustrative in defining strength differences which may occur between fill types. The grain shape properties and sharpness of particle edges results from crushing, concentration and transportation of fill materials during mill processing steps. Crushing often creates highly angular particles. Concentration and material transportation processes, however, have the effects of smoothing or rounding the particle edges. Where, for instance, the final transportation distances to disposal are relatively short, tailings particles may remain quite angular in aspect. Sample tailings particles were photographed at 100 x magnification, as illustrated in Figure 4.2. For each tailing material, evidence of angular, sharp-cornered configurations are illustrated. In relative terms, the Gallen material appears to evidence very sharp particle edges, whereas the Pamour particles appear to exhibit a more rounded, less angular appearance. The Pamour product is also illustrated to be comprised of a wide distribution of well-graded particle sizes; both the Matagami and Gallen tailings products, alternatively, exhibit only coarse- and fine-sized particles, with little intermediate size material present, as was indicated by the respective sieve size analyses.

4.3 Short Term Strength

The strength of frozen soils develops from cohesion, interparticle friction and particle interlocking as previously described in Section 3.2.1.

The tests described in this section were conducted to determine the optimum strength versus water constituent ratio for the three tailings products, mixed with water and frozen, either in the form of a tailings slurry or pelletized tailings, and

PAMOUR TAILINGS



100 um

MATAGAMI TAILINGS

100 um

GALLEN TAILINGS

100 um

FIGURE 4.2 Microscope Photos of As-Received Tailings Samples

TABLE 4.1

SUMMARY OF TAILINGS PHYSICAL PROPERTY TESTS

(ON DRY, AS-RECEIVED MATERIALS)

PARAMETER	TAILINGS MATERIAL		
	PAMOUR	MATAGAMI	GALLEN
DRY BULK DENSITY (g/cm^3)	1.30	1.80	2.19
TRUE SOLIDS DENSITY (g/cm^3)	2.81	3.81	4.73
DRY POROSITY (%)	53.7	53.0	53.7

failed under dynamic rates of strain.

4.3.1 Slurry Samples

The tests described in this section represent an attempt to determine the optimum tailings/water ratio, for frozen slurry samples, for each of the Pamour, Matagami and Gallen tailings products. Five water content levels, at 5%, 10%, 15%, 20% and 25% by weight, were selected. The water content infers the percentage of total manufactured sample weight (solid plus water weight, combined), as is customary within the mining industry.

Dry tailings materials were weighed and mixed with the required amounts of water to produce slurry mixtures which were subsequently poured into 5 cm Ø by 10 cm long PVC tubes, and stored within the Cold Environment Laboratory in evacuated, air-tight freezer bags for a period of 7 days, at a temperature of $-5.5^{o}C$. Temperatures were maintained continuously to within accurate limits of $\pm$ $0.5^{o}C$ during all tests. Specimens were failed, unconfined, on a Material Test System (MTS) servo-controlled compression loading frame under dynamic strain rate loading control at rates approximating $1.15 \times 10^{-3} s^{-1}$. Sample load and deformation variables were continuously monitored during failure tests and were utilized to develop failure parametric data for the frozen slurry tailings materials. Typical failure test conditions are illustrated in the photographs of Figure 4.3. A minimum sample population of ten (10), for each material type and moisture content condition, was tested. Upon completion of tests, results were averaged. Results of the short term (dynamic) unconfined compression tests are presented in Section 5.3.1 of this report.

Optimum water content conditions, for peak unconfined strength capability, were determined on the basis of slurry failure test results, and were used for the purpose of selecting pellet fabrication water content limits during long term creep test studies. For the sum of material types investigated, average tailings moisture content conditions approximating 15% were observed to mobilize very favourable strength results. For this reason, pelletized fill samples were thereafter to be fabricated at 15% moisture limits for additional test purposes.

4.3.2 Pelletized Samples

The concept of pelletizing tailings, and allowing them to freeze, prior to placement as underground support, offers several advantages over other means of handling and freezing tailings products. For the purpose of conducting short term (dynamic) strength evaluations on frozen, pelletized tailings materials, pellet samples of each of the as-received tailings products were fabricated (at 15% moisture levels) and stockpiled in total batch weights approximating 50 kg. Pellet batches, before sample casting, were stored in evacuated, air-tight freezer bags at a uniform temperature of $-5^{o}C$ for a minimum period of seven days within the Cold Environment Laboratory. Pellets were manufactured on a Dravo Laboratory Model Pelletizing Disk, 35 cm in diameter, powered by a 1/4 h.p. vari-drive motor. For all fabrication steps, the slope of the disk was maintained at 60^{o} from the horizontal and the speed at 16 rpm.

Dynamic strength tests were performed upon unconfined, frozen pellet masses which were initially created by casting frozen pellets into 10 cm diameter by 20 cm long cylindrical plastic forms. The fabricated cyclindrical pellets, at 15% moisture contents, were initially preconsolidated under 225 kg. loads, and were allowed to cure for a period of ten days at the regulated $-5^{o}C$ temperature level. A minimum of ten samples, of each tailings type, were manufactured for short term unconfined strength tests.

All pellet cylinders were extracted, undisturbed, from their confining molds and were then subjected to unconfined compression failure under dynamic, linearly-varying axial strain rates approximating $1 \times 10^{-3} S^{-1}$. A typical failure test condition is illustrated in the photograph of Figure 4.3.

The results of short term unconfined compression strength tests on cylinders of frozen pellet materials are presented in Section 5.3.2 of this report.

4.4 Creep Tests

Upon completion of short term strength tests, constant load tests were initiated on frozen mixtures of both pelletized and slurry tailings materials. In each case, optimum tailings

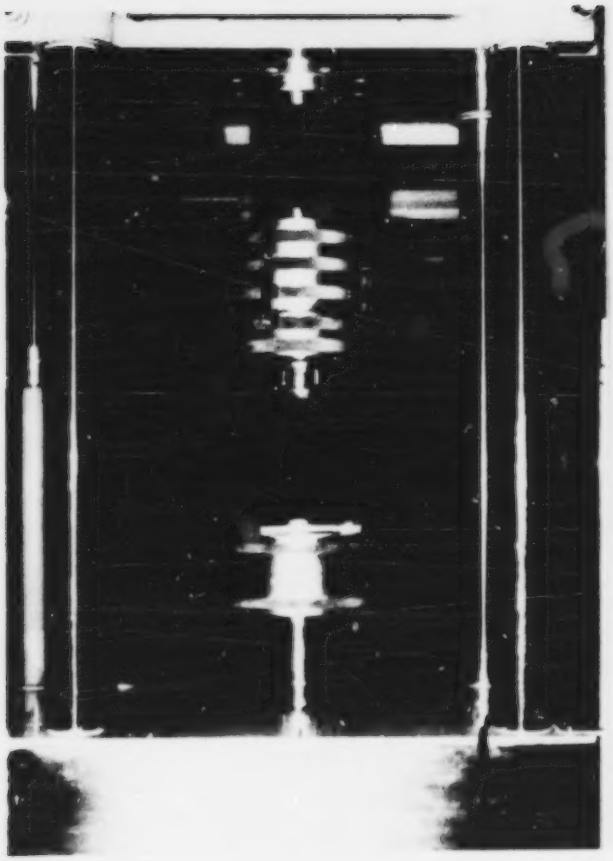


FIGURE 4.3: LABORATORY SETUP FOR FAILING SAMPLES UNDER DYNAMIC STRAIN RATES (PELLETIZED SAMPLES)

moisture content levels, approximating 15%, were utilized. At such levels, maximum short term unconfined strengths were previously recorded, and were similarly desired to be maintained during the constant load studies.

Constant load tests were conducted upon frozen slurry and pelletized tailings materials at various levels of consolidation, according to the results of dynamic strength tests. The laboratory apparatus employed for the constant load tests is shown in Figures 4.4 (a) and 4.4 (b) for slurry samples and pelletized samples, respectively.

4.4.1 Slurry Samples

Slurry sample constant load tests were performed upon cylindrical samples manufactured at 5 cm Ø by 10 cm long dimensions. A minimum of thirty samples of each tailings type were prepared, at the fixed 15% tailings moisture content, and were allowed to cure at a temperature of $-5^{o}C$ for uniform intervals of forty-eight hours prior to test use. Creep loads were arbitrarily selected at fixed percentages, equivalent to 50% and 30% respectively, of the sample unconfined dynamic failure load limits. One set of ten samples, of each tailings material, was subjected to creep loading at levels equivalent to 30% of the unconfined dynamic failure load while confinement within the PVC molds was maintained. A second set of each was loaded at 50% equivalent load levels under similar confinement. A third set was loaded incrementally at load levels initially equal to 30% of the equivalent failure load, then increased by 20% to the 50% level after secondary creep time/deformation behaviour had been visually achieved. Confinement was maintained by the use of PVC cylindrical molds in all cases.

Typical constant load data for slurry samples of each tailings type are discussed in section 5.3.1 of this report.

4.4.2 Pelletized Samples

Frozen pelletized fill sample constant load tests were performed upon 10 cm Ø by 20 cm long cylindrical samples, formed and cast in an identical fashion as per short term strength samples described in Section 4.3.2. Simiarly, a minimum total of

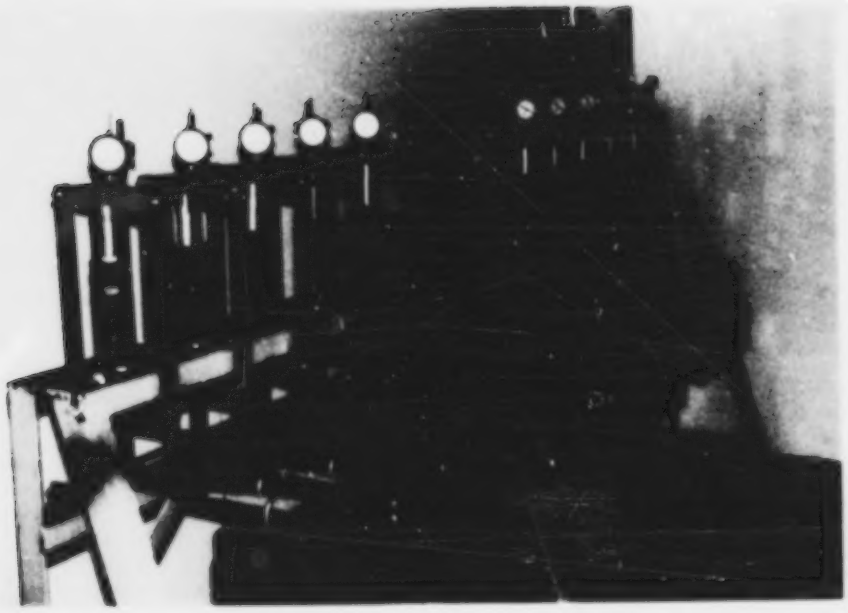


FIGURE 4.4 (a): LABORATORY APPARATUS FOR CONSTANT LOAD TESTS ON FROZEN SLURRY SAMPLES

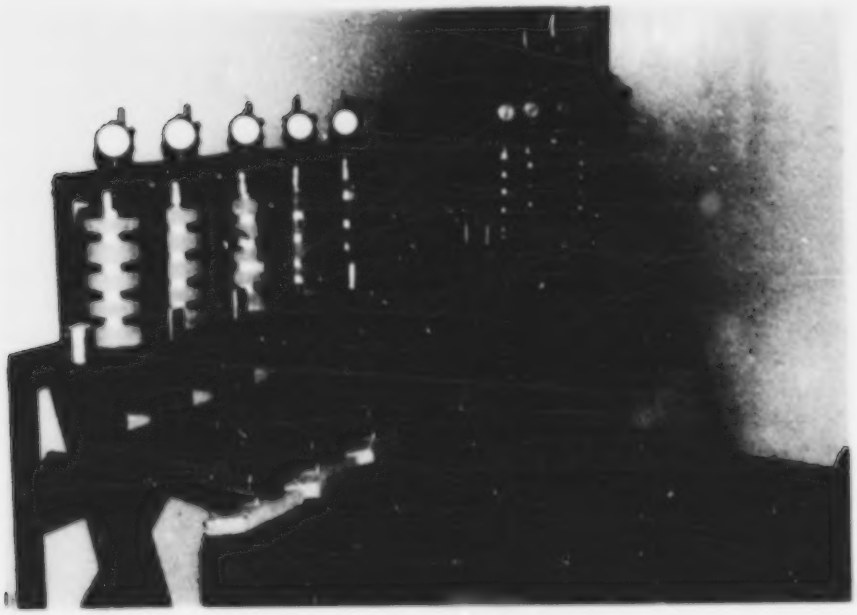


FIGURE 4.4 (b): LABORATORY APPARATUS FOR CONSTANT LOAD TESTS ON FROZEN PELLET SAMPLES

thirty samples of each tailings material type was prepared and allowed to cure at $-5^{\circ}C$ for uniform 48 hour intervals prior to loading. Constant loads equivalent to 30 and 50 percent of the equivalent unconfined pellet sample failure loads were maintained on confined samples of each constitutent tailings material. Ten samples of each respective tailings type were loaded at 30% load levels; similarly, a second ten samples of each tailings type were loaded at 50% load levels. A third set of each was subjected to incremental loading at the 30 and 50 percent levels, sequentially, in a similar fashion to that outlined for slurry sample tests in Section 4.4.1. Typical frozen pelletized fill constant load data is discussed in Section 5.3.2 of this report.

5.0 TEST RESULTS

5.1 Generalities

Three separate tailings materials were obtained from Pamour, Matagami and Gallen mines respectively. Microscope photos of the as-received tailings were shown in Figure 4.2, while Figure 4.1 shows grain size analysis of the materials. Sample physical characteristics were discussed in detail in Section 4 of this report.

Table 4.1 summarized basic physical properties of the tailings including apparent bulk density, solids density and porosity. It is important to notice the difference in solids density between Pamour and Gallen samples. All three materials exhibited roughly similar porosities approximating 53%.

Both slurried and pelletized frozen tailings samples were prepared and tested. For comparison purposes, slurried samples act as a base case since they are easier to compare to known materials such as frozen silts.

Conventional uniaxial strength tests were performed at strain rates approximating 10^{-3} sec^{-1} to provide "short-term" or dynamic strength data. These values, for each fill type, may be compared to expected field loadings mobilized by the heights of fill in a stope.

Long-term strength tests were conducted on both fill types in two phases, i) in confined tests to simulate underground stope wall confinement and ii) with initial confinement followed by confinement removal to simulate pillar mining adjacent to a backfilled stope.

5.2 Short Term Strength

Short term strength tests were done at strain rates of approximately 10^{-3} sec^{-1} on frozen slurried tailings specimens at varying water contents. Samples were tested at temperatures of $-5^{\circ}C$ and $-15^{\circ}C$ and these test data are summarized in Tables 5.1 and 5.2 respectively.

Figure 5.1 shows unconfined compressive strength versus

TABLE 5.1

SHORT TERM UNCONFINED FAILURE PROPERTIES OF FROZEN SLURRY MIXTURES ($-5^{o}C$)

SAMPLE	% H_2O	DEGREE OF SATURATION (Sr %)	FAILURE STRESS (MPa)	DENSITY (g/cm^3)	E (MPa)	PERCENT STRAIN TO PEAK LOAD CONDITION
PAMOUR	25	60.6	2.99	1.90	147.8	6.8
	20	48.5	3.60	1.85	175.0	7.1
	15	36.3	1.76	1.52	91.4	8.1
	10	24.2	0.13	1.32	11.2	3.5
	5	12.1	0.04	1.31	2.1	4.5
MATAGAMI	25	84.5	3.47	2.25	140.1	7.2
	20	67.6	3.74	2.44	173.7	7.1
	15	50.7	3.39	2.36	103.3	6.6
	10	33.8	0.88	2.01	30.5	5.8
	5	16.9	0.26	1.84	9.9	4.8
GALLEN	25	100	2.81	2.57	135.2	6.8
	20	81.6	2.85	2.70	116.2	6.3
	15	61.1	2.47	3.03	92.0	7.8
	10	40.8	1.41	2.69	66.4	4.8
	5	20.4	0.07	2.33	9.5	2.9

NOTE: All samples frozen at $-5^{o}C$ for 7 day cure period, and failed at axial strain rate of 1.15×15^{-3} s^{-1}.

TABLE 5.2

SHORT TERM UNCONFINED FAILURE PROPERTIES

OF FROZEN SLURRY MIXTURES (-15°)

SAMPLE	% H_2O	FAILURE STRESS (MPa)	DENSITY (g/cm^3)	E (MPa)	PERCENT STRAIN TO PEAK LOAD CONDITION
PAMOUR	25	8.27	1.90	514.5	4.9
	20	5.58	1.76	346.6	5.0
	15	1.69	1.39	72.8	6.3
	10	0.53	1.34	43.0	4.8
	5	0.11	1.33	9.7	2.5
MATAGAMI	25	4.58	2.29	108.8	7.9
	20	5.98	2.47	348.3	5.2
	15	4.94	2.40	253.2	6.3
	10	1.50	2.03	94.7	4.5
	5	0.25	1.85	14.8	3.4
GALLEN	25	8.13	2.85	208.3	6.5
	20	7.61	2.78	405.5	4.1
	15	9.34	3.21	447.4	5.0
	10	4.79	2.80	331.6	2.9
	5	0.68	2.30	57.6	2.0

NOTE: All samples frozen at -5°C for 7 day cure period, and failed at axial strain rate of 1.15×15^{-3} s^{-1}.

water content data. The data shows the considerable effect of temperature on strength whereby decreasing temperature mobilizes increasing strength. The data also indicates an "optimum moisture content" between 15% to 20% for the tailings materials. Pelletized samples were then produced at 15% moisture content.

Figure 5.2 shows compressive strength data versus degree of saturation. It should be noted that only the Gallen tailings were tested at 100% saturation. The maximum test sample saturation for Pamour and Matagami samples are 60% and 80% respectively. The degree of saturation for samples used for long term constant load tests varied from about 35% to 60%.

Pelletized tailings samples were produced in the laboratory at a moisture content of about 15% and were tested for short term unconfined compressive strength at a strain rate of 1×10^{-3} sec^{-1}. Table 5.3 lists the average short term unconfined compressive strength data for each pelletized tailings type, as determined from the above testing. The measured strength values vary between 0.3 and 0.55 MPa. The measured peak strength for frozen pelletized samples is therefore only 15% to 20% of the strength determined at optimum moisture content for the slurried tailings specimens.

5.3 Constant Stress Tests

Long term strength (constant load) tests were performed on both frozen slurried and frozen pelletized samples. The tests were designed to roughly simulate in-situ backfill conditions. The laboratory apparatus and procedures were discussed in detail earlier in this report. Tailings samples were mixed at 15% water contents and were frozen at a temperature of $-5^{\circ}C$. Constant load test results for frozen slurried and pelletized samples respectively are discussed in the following sections.

5.3.1 Frozen Slurried Samples

Slurried tailings samples were prepared as described in Section 4.3.1 of this report and were loaded at levels equivalent to those necessary to mobilize 30% and 50% of the dynamic unconfined strength conditions at similar water content. Table 5.4 lists the loads used for the long term tests and the effective fill heights that these loads represented for each tailings type, at known bulk density conditions.

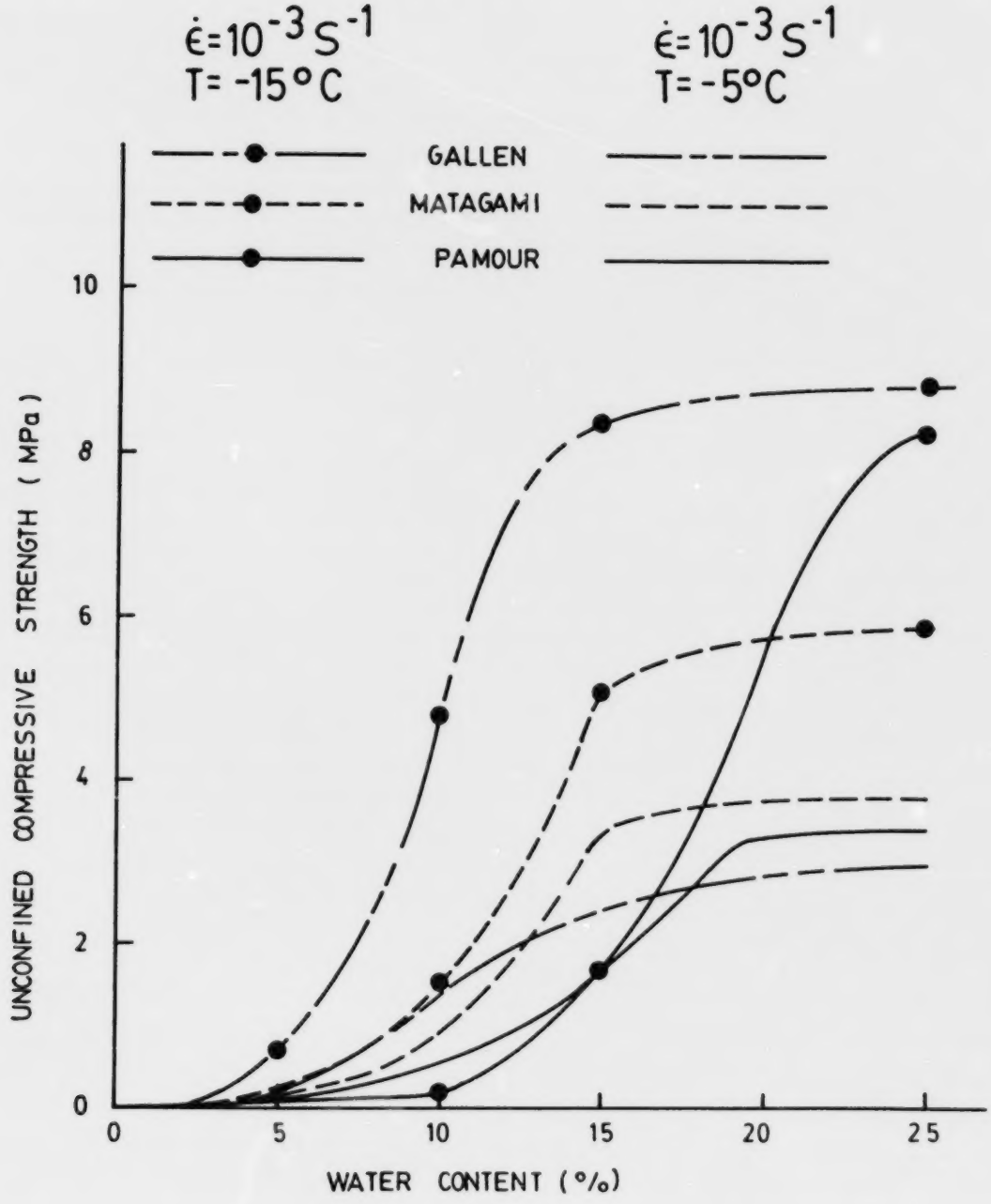


FIGURE 5-1 - UNCONFINED COMPRESSIVE STRENGTH OF FROZEN SLURRIED TAILINGS VS. WATER

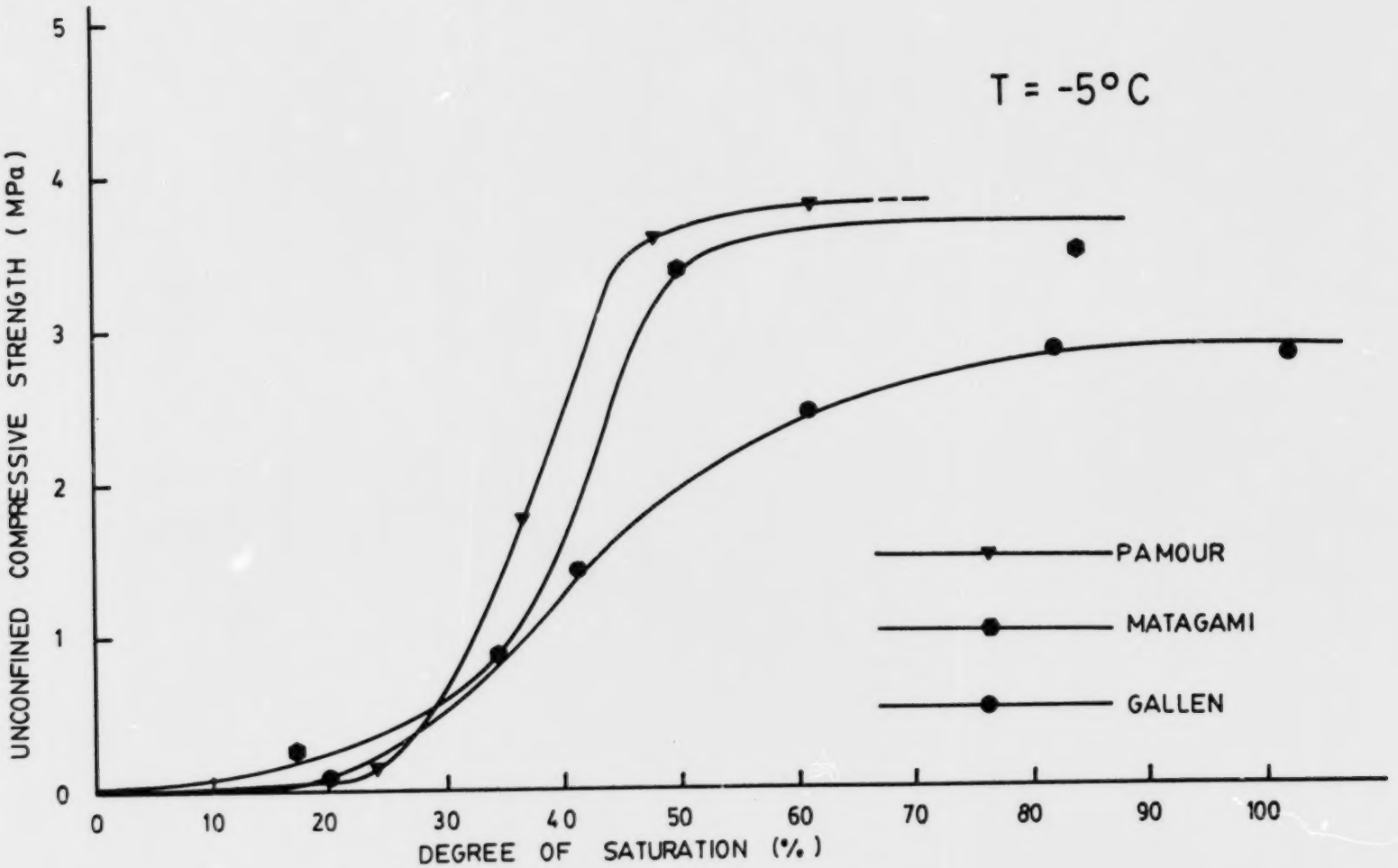


FIGURE 5-2 - UNCONFINED COMPRESSIVE STRENGTH VERSUS DEGREE OF SATURATION FOR FROZEN TAILINGS SLURRY

TABLE 5.3

UNCONFINED SHORT TERM STRENGTH TEST RESULTS FOR

FROZEN PELLETIZED TAILINGS SAMPLES

TAILINGS TYPE	BULK DENSITY (g/cm^3)	UNCONFINED STRENGTH (MPa)
MATAGAMI	1.57	0.32
PAMOUR	1.19	0.31
GALLEN	2.05	0.55

TABLE 5.4

CREEP TEST LOAD APPLICATIONS FOR

FROZEN SLURRY SAMPLES

TAILINGS TYPE	% SHORT TERM U.C.S.	LOAD (KPa)	EFFECTIVE FILL HEIGHT (m)
PAMOUR	50%	880	59
MATAGAMI	50%	1695	75
GALLEN	50%	1235	42
PAMOUR	30%	528	35
MATAGAMI	30%	1017	44
GALLEN	30%	741	25

Confined samples were subjected to such loading conditions to simulate fill placement, under confinement, within a stope. The results of these tests, in terms of axial strain versus time plots, are summarized in Figures 5.3 and 5.4 for load equivalent levels equal to of 30% and 50% of the short term strength loads respectively.

Confined, constant load tests were continued until linear time-dependent deformation was established, at which time confinement was removed. The above tests were run to simulate mining a pillar adjacent to a stope backfilled with frozen tailings. Test results of confinement removal for frozen slurried Pamour and Matagami tailings are shown in Figures 5.5 and 5.6.

5.3.2 Frozen Pelletized Samples

Pellet tailings samples were prepared as described in Section 4.3.2 of this report. Constant load tests were then implemented at load levels equivalent to 30% and 50% of those necessary to yield the dynamic unconfined strength for each material. Loads used for these frozen, pelletized fill tests are listed in Table 5.5.

All of the pelletized fill tests were initially done in anchored molds to simulate full wall confinement. Once linear strain-time behaviour was achieved, confinement was removed to simulate loss of lateral wall restraint which is associated with pillar mining. Test data for the Gallen, Matagami and Pamour pelletized samples are summarized in Figures 5.7, 5.8 and 5.9 respectively.

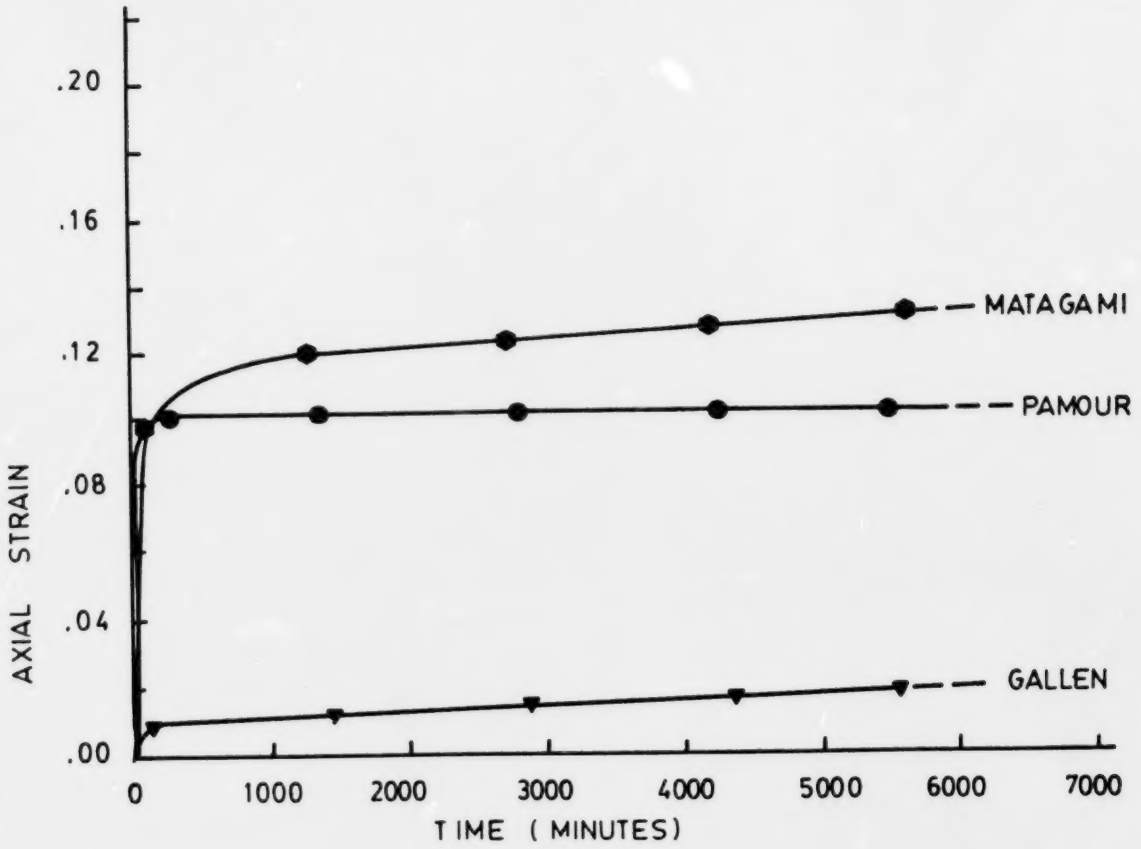


FIGURE 5-3 - AVERAGE LINEARIZED CREEP CURVES FOR TAILINGS MATERIALS AT 30 % FAILURE LOAD (-5° C)

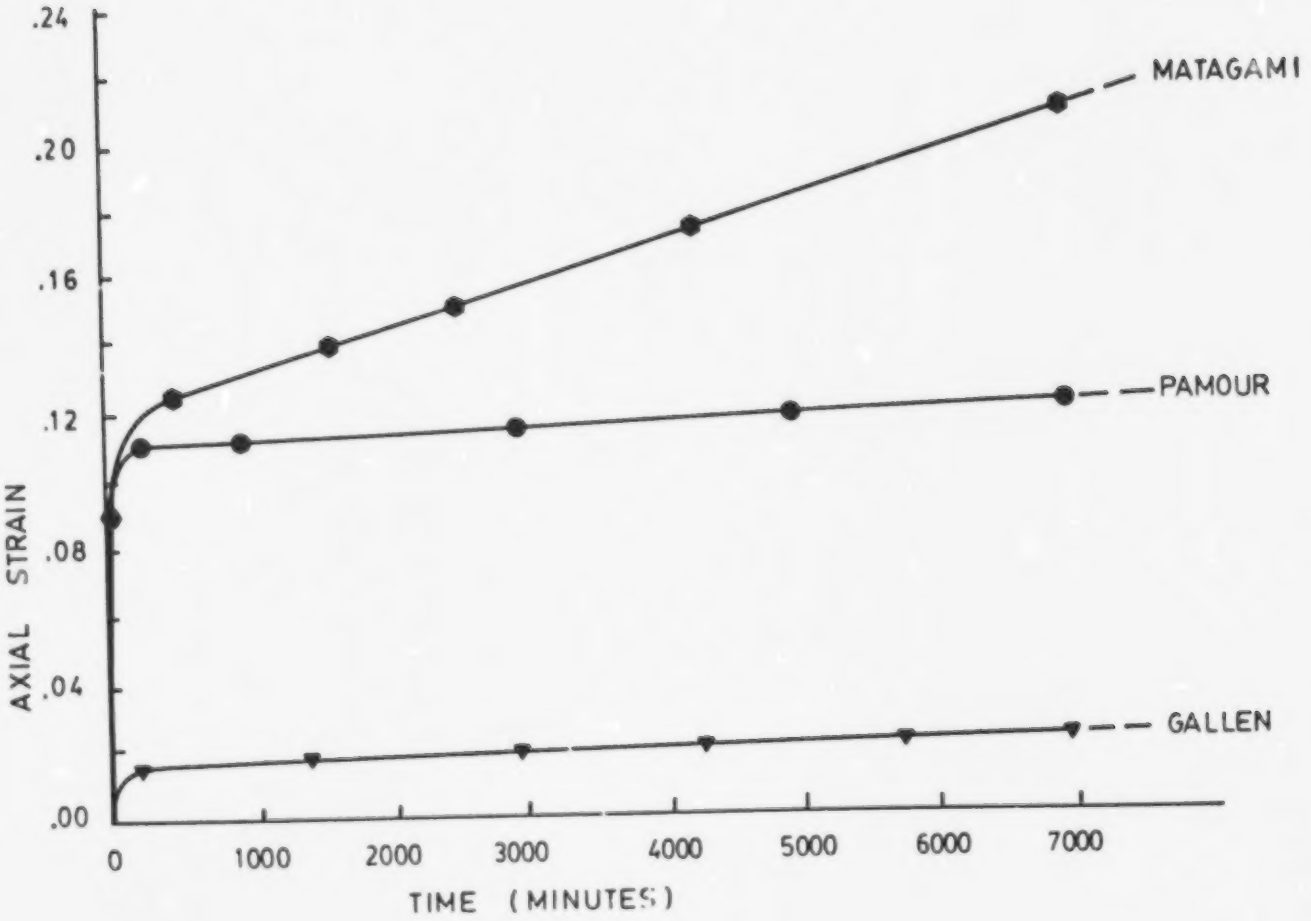


FIGURE 5-4 - AVERAGE LINEARIZED CREEP CURVES FOR TAILINGS MATERIALS AT 50 % FAILURE LOAD (- 5° C)

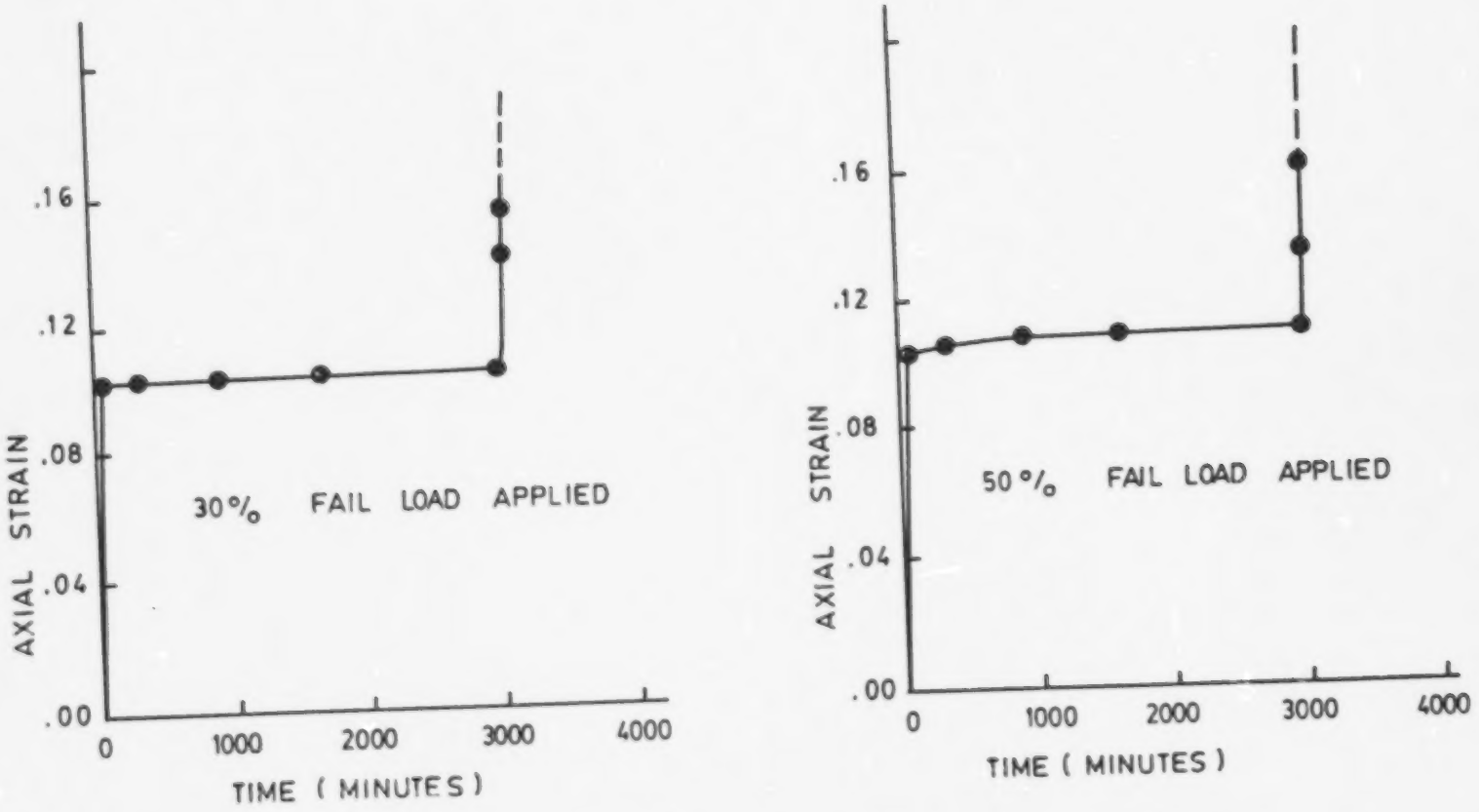


FIGURE 5-5 - AVERAGE CREEP CURVES FOR FROZEN PAMOUR SLURRY SAMPLES, INITIALLY HELD CONFINED THEN RELEASED (-5°C)

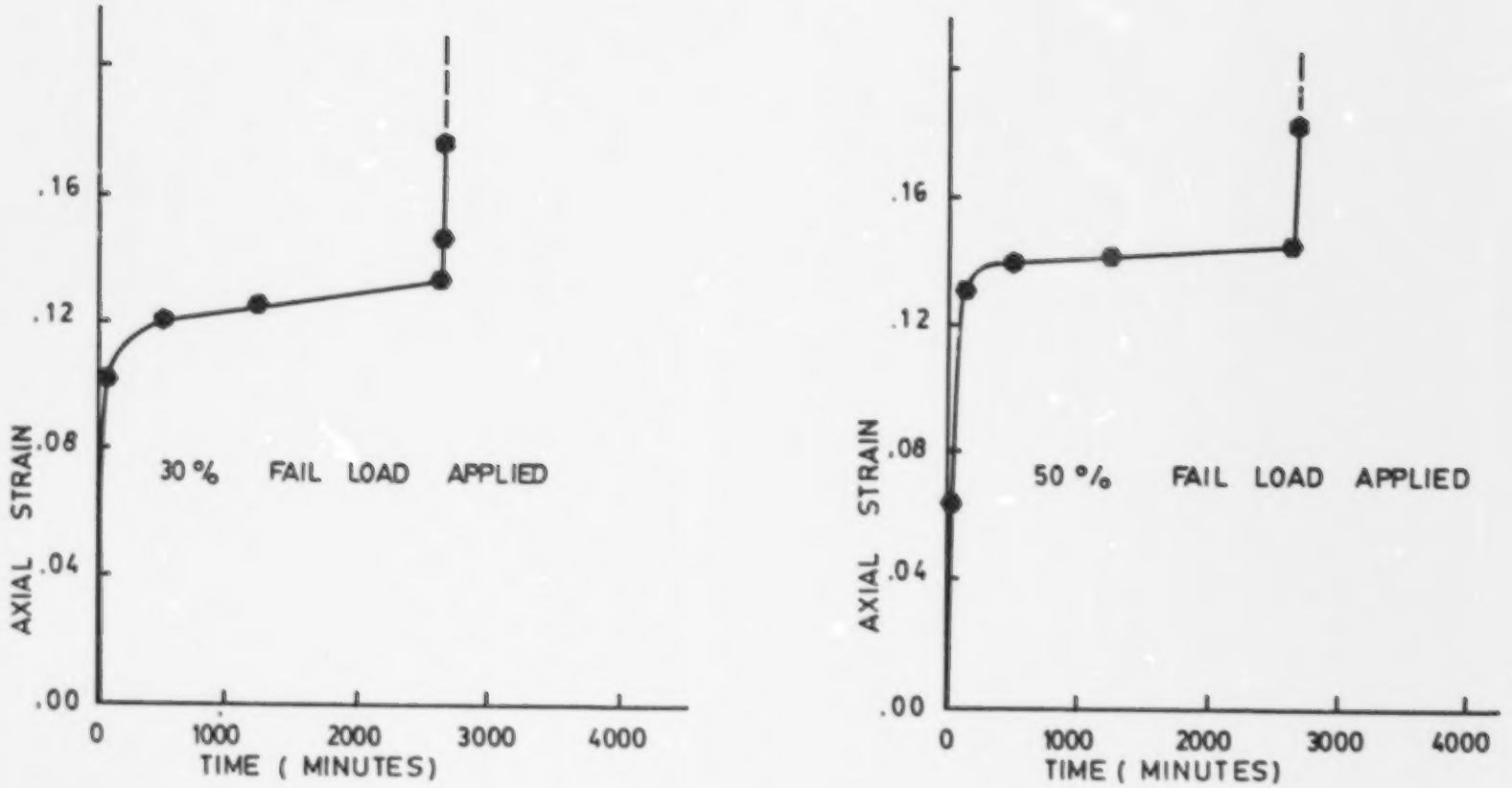


FIGURE 5-6 - AVERAGE CREEP CURVES FOR FROZEN MATAGAMI SLURRY SAMPLES, INITIALLY HELD CONFINED THEN RELEASED (- 5°C)

TABLE 5.5

CREEP TEST LOAD APPLICATIONS FOR

FROZEN PELLETIZED FILL SAMPLES

TAILINGS TYPE	% SHORT TERM U.C.S.	LOAD (KPa.)	EFFECTIVE FILL HEIGHT (m)
PAMOUR	30%	90	7.9
MATAGAMI	30%	100	6.3
GALLEN	30%	170	8.2
PAMOUR	50%	150	13.2
MATAGAMI	50%	160	10.5
GALLEN	50%	280	13.8

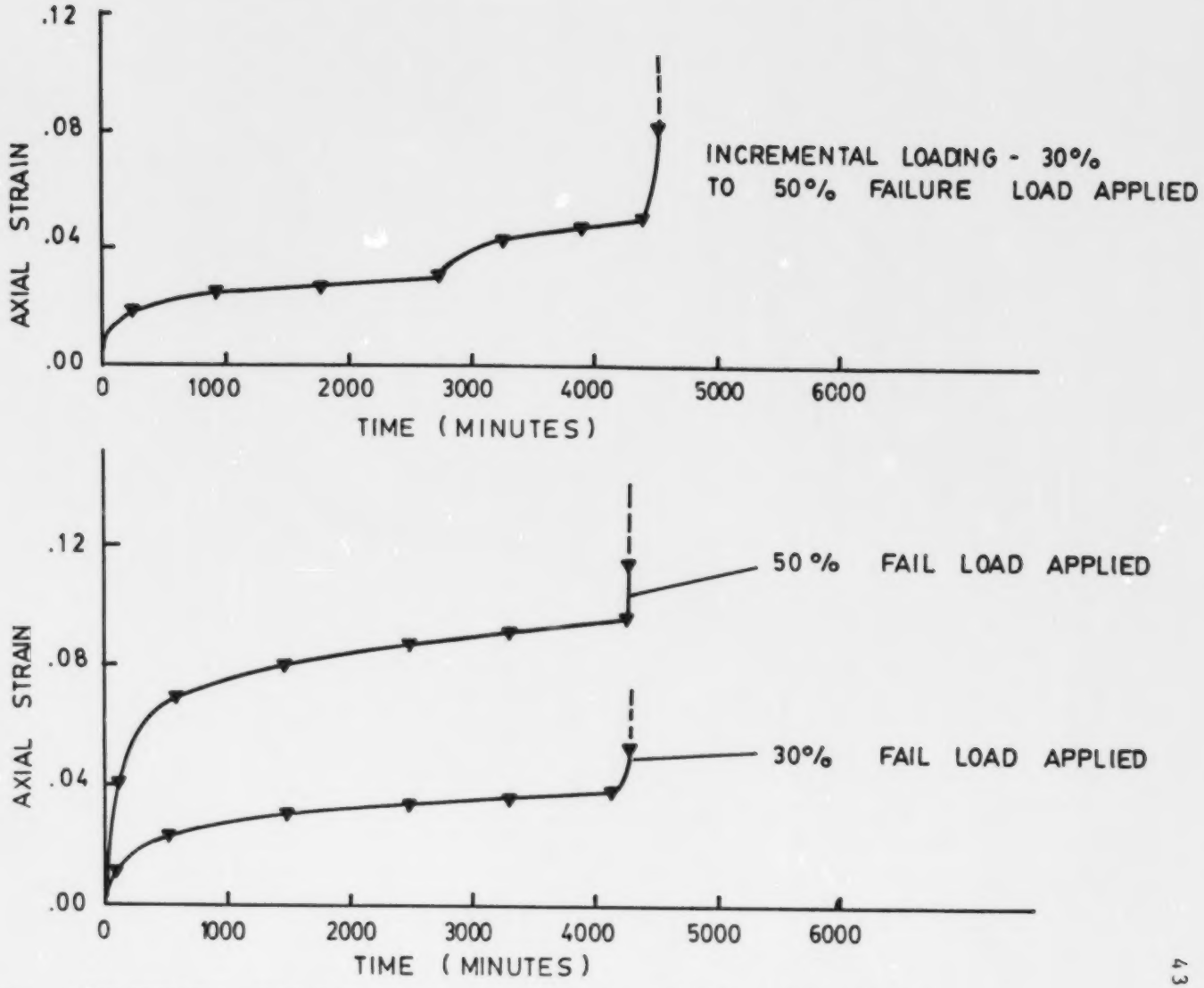


FIGURE 5.7 - CREEP TEST BEHAVIOUR FOR FROZEN PELLETIZED GALLEN TAILINGS MATERIAL

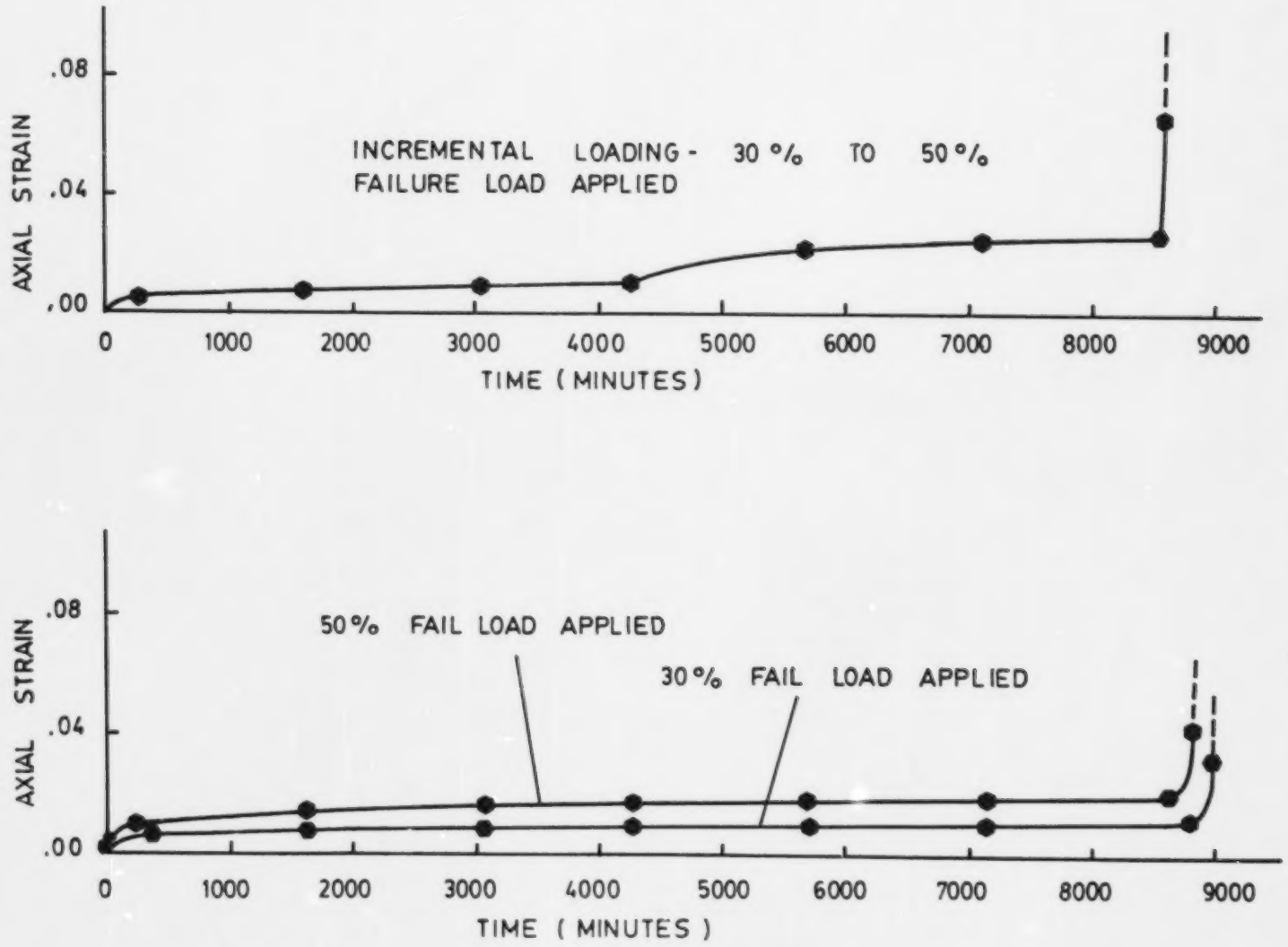


FIGURE 5.8- CREEP TEST BEHAVIOUR FOR FROZEN, PELLETIZED MATAGAMI TAILINGS MATERIAL

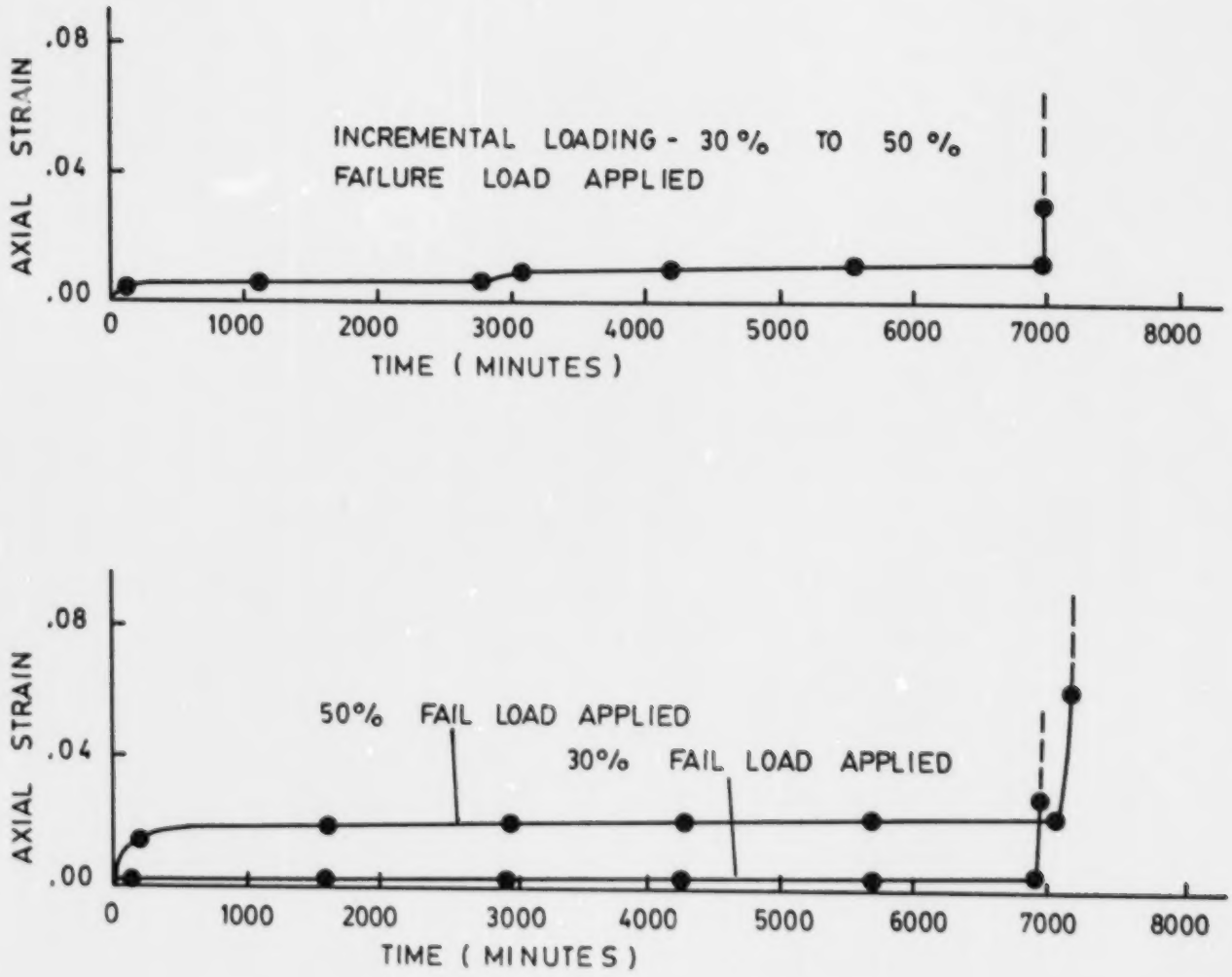


FIGURE 5.9 - CREEP TEST BEHAVIOUR FOR FROZEN PELLETIZED PAMOUR MATERIAL

6.0 CONCLUSIONS AND RECOMMENDATIONS

The present test program was initiated to evaluate those parameters of frozen slurried and pelletized tailings critical to their use as an engineered mine backfill. Constant load tests were specified since this test condition was considered to best simulate anticipated loading conditions underground. The test procedure was also designed to simulate the mining sequence. It was anticipated that "creep" test strength parameters could then be used to predict material behaviour under various mining conditions. It was also attempted to follow standard frozen soil test procedures used in civil engineering practice. Strength properties of frozen tailings could then also be compared with known properties of frozen soils as discussed in Section 3.2 of this report.

For the above reasons dynamic (high strain rate) tests were done on frozen slurry and pelletized samples in order to determine the instantaneous unconfined compressive strength, c, (U.C.S.). Constant load tests were then done at various percentages of the above U.C.S., in this case at levels equivalent to 30% and 50% of the failure load levels.

A major difference between most frozen soils and frozen tailings results from the degree of ice saturation. Frozen soils are usually fully saturated. Unfrozen tailings backfills however are designed to be free draining and are not placed in a saturated condition for safety reasons. In the present study frozen slurried tailings were tested at various water contents, and an "optimum water content" of 15% to 20% was determined. This optimum water content occurs where maximum U.C.S. values are obtained (Figure 5.3). The degree of saturation for the above samples varied from 50% to 80%. The short term U.C.S. slurry tailings tests indicated strength dependence on temperature (Figure 5.1) and on the degree of total sample saturation (Figure 5.2). The dynamic tests also indicate a much lower strength for frozen pelletized samples than for frozen slurried tailings.

Constant load tests were then done in two distinct phases in order to simulate in-situ mine conditions. In the first phase samples were tested in a confined condition in order to simulate full stope confinement. Confined tests were continued until constant deformation-time rates were obtained. Confinement was

then released to simulate pillar extraction.

Phase 1 of the constant load tests all resulted in very low deformation-time rates at both 30% and 50% of the U.C.S. When confinement was removed however, (Phase II), all samples, both slurried and pelletized, failed almost immediately (Figures 5.5, 5.6, 5.7, 5.8 and 5.9). This is illustrated, as well, in the photographs of Figures 6.1 and 6.2(a) and (b).

It was considered that the above constant load strength data might indicate a strain rate dependence of the U.C.S. for frozen tailings. Some degree of strain rate dependence has been observed for both frozen soil and pure ice, (reference, Section 3.2 of this report). For this reason frozen slurry samples of Pamour tailings were tested at various strain rates and water contents. The results are shown in Figure 6.3. The data indicates that the U.C.S. is dependent on water content and very strongly dependent on strain rate. For Pamour tailings, the U.C.S. decreases to nearly zero at a strain rate of 10^{-5} sec^{-1} irrespective of ice saturation levels. Strain rates of 10^{-5} sec^{-1} or less are considered realistic for anticipated long term load rates on backfill underground.

Strength data for a frozen silt is also shown in Figure 6.3 for comparison with the Pamour frozen tailings. The frozen silt shows considerably higher strength than the frozen tailings. The frozen tailings have a much higher bulk porosity, (53% vs 35% for silt), and much lower degree of saturation than the frozen silt. Figure 6.4 is a phtograph of the frozen slurry showing the high bulk porosity of samples, evidenced by air voids or bubbles. The above differences are probably responsible for the observed strength differences.

The data in Figure 6.3 explains the observed failure of the frozen tailings samples since the applied constant loads were much higher than the material U.C.S. for samples tested at the low strain rates. Loads applied to the slurried tailings samples are representative of "reasonable" stope heights, (24 m to 75 m limits). Constant loads applied to the frozen pelletized samples however represent effective fill heights of only 6 m to 14 m. Such fill heights are much smaller than normally recommended stope heights which can reasonably be expected to exist in mining backfill situations.

It can be concluded that frozen pelletized mine tailings is not a competent backfill material to use in underground mines if the recovery of pillars is to be contemplated. On the other hand, frozen slurried tailings, similar to those tested, could remain exposed over heights reaching 75 m; the placement of slurries underground with subsequent in-situ freezing, may generate several technical difficulties.

The authors recommend that similar tests be conducted on broken ice fills; broken ice, in a mining situation, could be obtained from nearby lakes and transported to the mine site, then placed underground via a series of bored raises. This alternative to frozen tailings could be very inexpensive and should be assessed for future potential use by the industry.

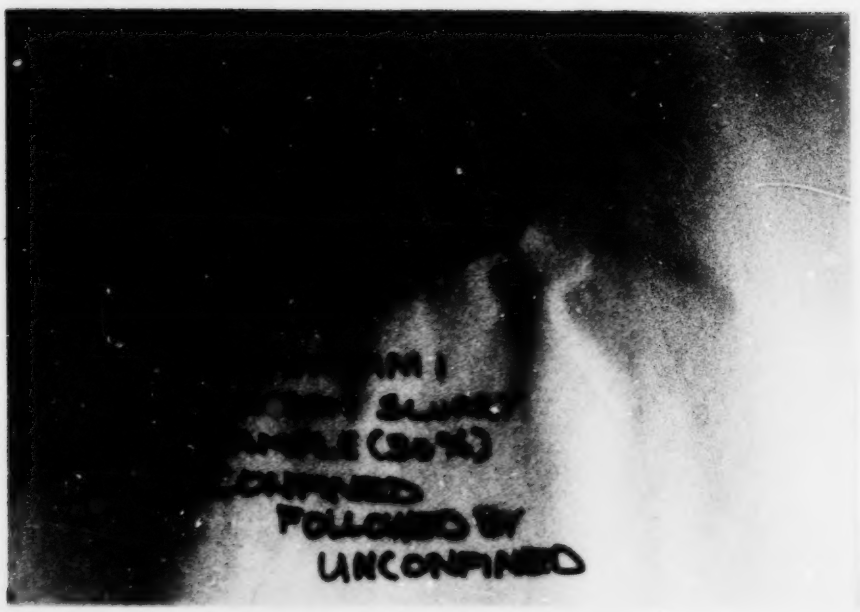


FIGURE 6.1: MATAGAMI FROZEN SLURRY SAMPLE UNDER CONSTANT LOAD TEST AND REMOVAL OF CONFINEMENT

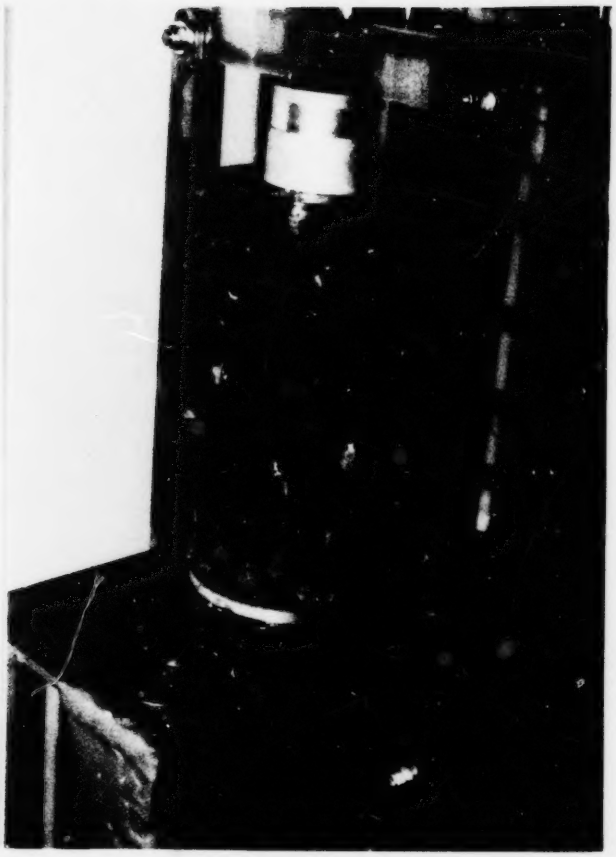


FIGURE 6.2 (a): MATAGAMI PELLET SAMPLE IN A CONSTANT LOAD TEST IMMEDIATELY AFTER CONFINEMENT REMOVAL

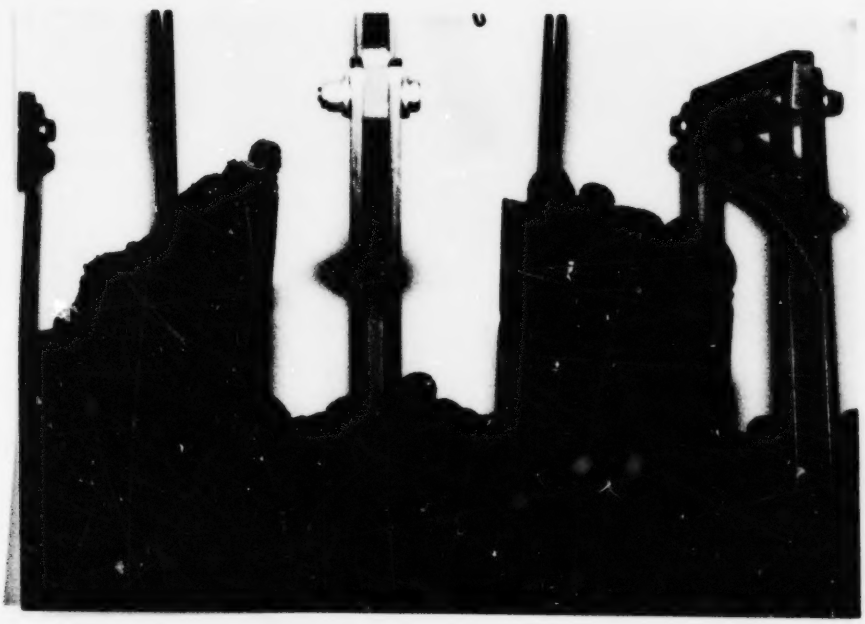


FIGURE 6.2 (b): MATAGAMI PELLET SAMPLE SEVERAL MINUTES AFTER CONFINEMENT REMOVAL

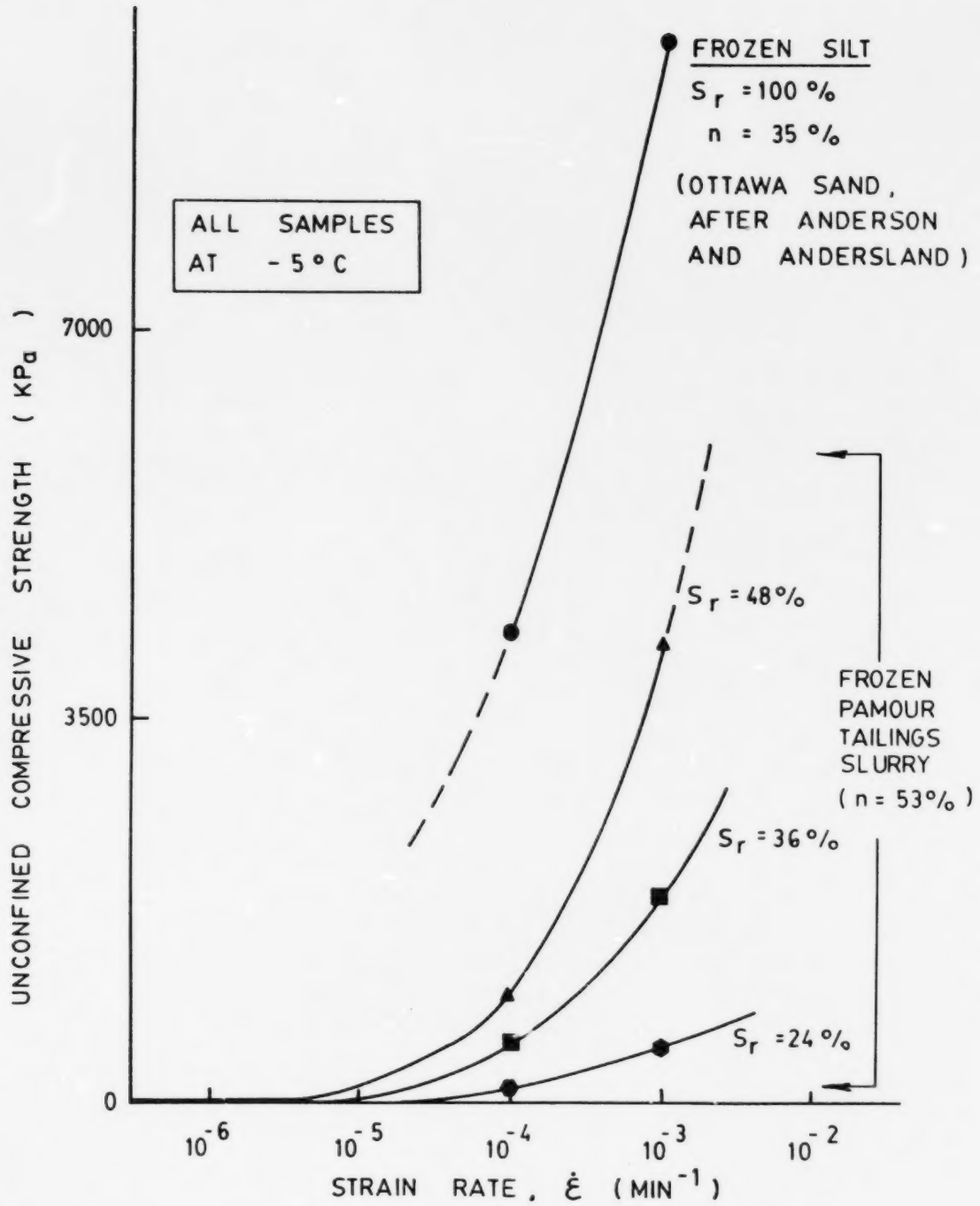


FIGURE 6.3 - STRAIN RATE DEPENDENCE ON UNCONFINED COMPRESSIVE STRENGTH OF FROZEN SAND

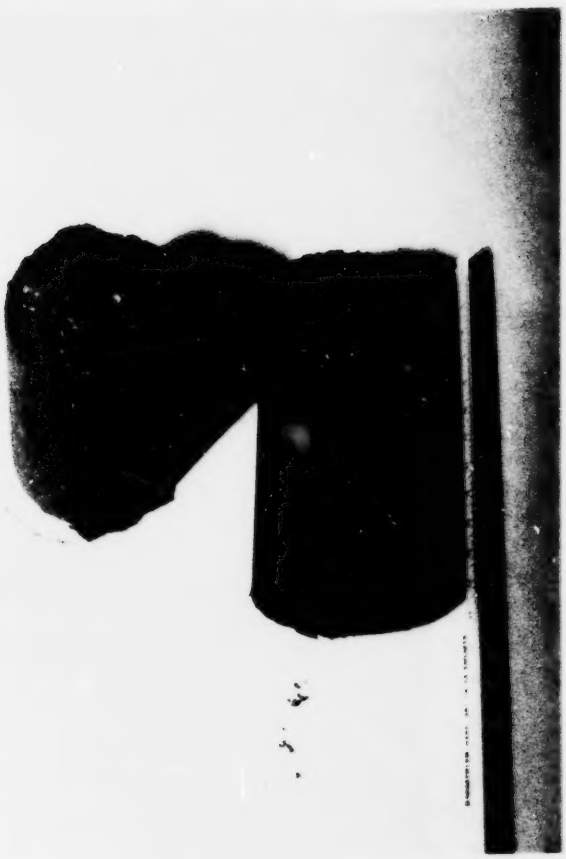


FIGURE 6.4: FROZEN SLURRY SAMPLE SHOWING HIGH BULK POROSITY EFFECTS INDUCED BY VOID INCLUSIONS

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